

Detecting Stellar Spots by Gravitational Microlensing

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ABSTRACT

During microlensing events with a small impact parameter the amplification of the source flux is sensitive to the surface brightness distribution of the source star. Such events provide a means for studying the surface structure of target stars in the ongoing microlensing surveys, most efficiently for giants in the Galactic Bulge. In this work we demonstrate the sensitivity of point-mass microlensing to small spots with radii $r_s \lesssim 0.2$ source radii. We compute the amplification deviation from the light curve of a spotless source and explore its dependence on lensing and spot parameters. During source-transit events spots can cause deviations larger than 2%, and thus be in principle detectable. Maximum relative deviation usually occurs when the lens directly crosses the spot. Its numerical value for a dark spot with sufficient contrast is found to be roughly equal to the fractional radius of the spot, i.e. up to 20% in this study. Spots can also be efficiently detected by the changes in sensitive spectral lines during the event. Notably, the presence of a spot can mimic the effect of a low-mass companion of the lens in some events.

Subject headings: gravitational lensing — stars: spots

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1. Introduction

Apart from having a venerable history (Schwarzschild 1975), the question of small-scale surface structure in normal stars is very important for stellar modeling. Direct interferometric evidence is scarce and inconclusive (Di Benedetto & Bonneau 1990; Hummel et al. 1994). Indirect evidence, such as Doppler imaging and photometry, is limited to specific types of stars (RS CVn, BY Dra, etc.). Photometric evidence for stellar spots comes from the OGLE survey of Bulge giants (Udalski et al. 1995). Modeling of the spots on the stars selected from the OGLE database was reported by Guinan et al. (1997). Direct evidence for a bright spot is available for one red supergiant - α Ori (Uitenbroek, Dupree, & Gilliland 1998), although in this case the bright region may be associated with the long-period pulsation of the star. The evidence for spots is particularly scarce for normal red giants. Such information will be invaluable, given the current difficulty in calculating detailed red giant atmosphere models directly or extrapolating them from available dwarf models.

The presence of spots can also be revealed by observations of Galactic microlensing events. During such an event the flux from a background star is amplified by gravitational lensing due to a massive object, such as a dim star, passing in the foreground. Over 350 such events have been observed already, primarily toward source stars in the Galactic Bulge and the Magellanic Clouds. For a review of Galactic microlensing see Paczyński (1996). In events with a small impact parameter, when the lens passes within a few stellar radii of the line of sight toward the source, the lens resolves the surface of the background star, as the amplification depends on its surface brightness distribution. This effect is described in detail by Heyrovský, Sasselov, & Loeb (1999; hereafter HSL) for the case of a spotless source star. In this complementary work we study the case when the circular symmetry of the surface brightness distribution of the source is perturbed by the presence of a spot. We illustrate the effect using a model of the source of the MACHO Alert 95-30 event (hereafter M95-30; see Alcock et al. 1997). During this microlensing event the lens directly transited a red giant in the Galactic Bulge. As red giants in the Bulge are generally the most likely sources to be resolved, Galactic microlensing appears to be ideally suited for filling a gap in our understanding of their atmospheres as well as of spots in general.

In the following section we study the broad-band photometric effect of a spot on the light curve of a microlensing event. The spectroscopic signature on temperature-sensitive lines is illustrated in §3. In §4 we discuss the limitations of the simple spot model used here, as well as the possibility of confusing the effect of a spot with a planetary microlensing event. Our main results are summarized in §5.

2. Effect of a Spot on Microlensing Light Curves

We describe the lensing geometry in terms of angular displacements in the plane of the sky. The angular radius of the source star serves as a distance unit in this two-dimensional description.

During a point-mass microlensing event the flux from a spotless star with a limb darkening profile $B(r)$ is amplified by a factor

$$A_*(\vec{r}_L) = \frac{\int B(r) A_0(|\vec{r} - \vec{r}_L|) d\Sigma}{\int B(r) d\Sigma} \quad . \quad (1)$$

Here \vec{r}_L is the displacement of the lens from the source center, \vec{r} is the position vector of a point on the projected surface of the star Σ , and the point-source amplification is

$$A_0(\tau) = \frac{\tau^2 + 2\epsilon^2}{\tau\sqrt{\tau^2 + 4\epsilon^2}} \quad . \quad (2)$$

The Einstein radius of the lens¹ is denoted by ϵ , the separation between a point-source and the lens is τ .

At large separations \vec{r}_L , formula (1) is well approximated by the point-source limit (2). However, when the lens approaches the source closer than three source radii, finite-source effects become observable (higher than 1–2%), as shown in HSL. The light curve of such an event then contains information on the surface structure of the source, introduced through its dependence on the surface brightness $B(\vec{r})$. HSL dealt with spectral effects due to the wavelength-dependence of $B(r)$ in the case of a spotless source. Here we study the case of a source in which the circular symmetry is perturbed by a spot.

In such a case it is useful to separate the surface brightness distribution into the circularly symmetric component $B(r)$ (describing the source in the absence of the spot) and a brightness decrement $B_D(\vec{r})$. This decrement is zero beyond the area of the spot Σ' . The amplification of the spotted star can now be written

$$A(\vec{r}_L) = \frac{\int B(r) A_0(|\vec{r} - \vec{r}_L|) d\Sigma - \int B_D(\vec{r}') A_0(|\vec{r}' - \vec{r}_L|) d\Sigma'}{\int (B - B_D)(\vec{r}) d\Sigma} \quad , \quad (3)$$

here we made use of the linearity of the integral in the numerator in B . Note that the second integral in the numerator is taken only over the area of the spot. The position vector

¹ also in source radius units

\vec{r}' of a point within the spot as defined here originates at the source center. The relative deviation of the amplification (3) from the amplification of a spotless source (1) is

$$\delta(\vec{r}_L) = \frac{A - A_*}{A_*}(\vec{r}_L) = \frac{\int B_D(\vec{r}') d\Sigma'}{\int (B - B_D)(\vec{r}) d\Sigma} \left[1 - \frac{\int B_D(\vec{r}') A_0(|\vec{r}' - \vec{r}_L|) d\Sigma'}{A_*(\vec{r}_L) \int B_D(\vec{r}') d\Sigma'} \right] \quad (4)$$

We employ a simple model for a small spot by using a constant decrement B_D over a circular area with radius $r_s \ll 1$, centered at a distance s from the source center². This way we can compute both integrals in the numerator of expression (3) using the method for computing light curves of circularly symmetric sources described in Heyrovský & Loeb (1997). The expression for the amplification deviation in this model simplifies to

$$\delta(\vec{r}_L) = \frac{\pi r_s^2 B_D}{\int (B - B_D)(\vec{r}) d\Sigma} \left[1 - \frac{\int A_0(|\vec{r}' - \vec{r}_L|) d\Sigma'}{\pi r_s^2 A_*(\vec{r}_L)} \right] \quad (5)$$

In the following we illustrate the effect of a test spot superimposed on a spotless model of the M95-30 red giant source. The 3750 K model atmosphere applied here is described in more detail in HSL. In most of the applications we use its V-band limb-darkening profile for the surface brightness distribution $B(r)$. The presented broad-band results however do not change *qualitatively* for different spectral bands or source models in the small spot regime explored here.

The value of the brightness decrement B_D depends on the physical properties of the spot, as well as its apparent position on the source disk. We can separate these two by expressing the decrement as $B_D = (1 - \mu^{-1})B(s)$. Here we introduced the contrast parameter μ , which is equal to the ratio of the spotless brightness at the position of the center of the spot $B(s)$ to the actual brightness at the same position $B(s) - B_D$. The dependence of μ on the spot position s is weak except very close to the limb, we therefore neglect it here. The parameter μ now depends purely on intrinsic physical properties - namely on the temperature contrast of the spot ΔT , the effective temperature of the star and the spectral band. Its value can be obtained numerically by comparing model atmospheres of different temperatures. For example, $\mu = 10$ approximately for a $\Delta T = 1000$ K spot on the model source used. Values $\mu < 1$ can be used to describe bright spots, $\mu = 1$ corresponds to zero contrast.

Sample light curves computed using formula (3) are presented in Figure 1. In all cases a lens with the M95-30 Einstein radius of $\epsilon = 13.23$ transits the source star with zero impact

² Note that in this model the surface brightness within the spot is not constant, it decreases toward the limb of the source following the shape of the spotless profile $B(r)$.

parameter. The spot has a radius $r_s = 0.2$ and contrast $\mu = 10$. When the lens directly crosses the spot (solid line; spot centered at $s = 0.4$), there is a significant dip in the light curve. On the other hand, if the spot lies further from the lens path (dashed line; closest approach to spot = 0.3, $s = 0.5$) the effect is weak. It consists primarily of a slight shift due to the offset center of brightness, and a minor increase in peak amplification.

To explore the range of possible spot signatures on light curves we study the relative amplification deviation using equation (5). The deviation is primarily a function of parameters describing the lensing and spot geometries ($\vec{r}_L, \epsilon, s, r_s$), and the spot contrast μ - six parameters in all. The dependence of δ on the lens position \vec{r}_L is illustrated by the contour plots in Figure 2, for different spot positions s . The three other parameters are kept fixed at values $\epsilon = 13.23$, $r_s = 0.2$ and $\mu = 10$. First we note that the deviation from the spotless light curve of the same source can be positive as well as negative, for any spot position³. The negative effect peaks at 18–19% at the spot position in all four cases. This region of the source is relatively dimmer than in the spotless case. The weaker positive effect (2–3%, less when $s = 0$) peaks on the opposite side of the source close to the limb, a region relatively brighter than in the spotless case. Geometrically the actual deviation depends on the interplay of the distances of the lens from the spot, from the positive peak and from the limb.

Deviation curves for any particular lensing event with the given spot geometry can be read off directly from the plots in Figure 2. Examples corresponding to the four lens paths marked in Figure 2 are shown in Figure 3. Orienting our coordinate system as in Figure 2 with the spot along the positive x -axis, we parametrize the lens trajectory $\vec{r}_L = (x_L, y_L) = (p \sin \beta + t \cos \beta, -p \cos \beta + t \sin \beta)$, where t is the time in units of source-radius crossing time measured from closest approach. The parameter β is the angle between the spot position vector \vec{s} and the lens velocity $\dot{\vec{r}}_L$. In this notation the impact parameter p is given a sign depending on the lens motion - positive if \vec{r}_L turns anti-clockwise, negative if clockwise. The upper left panel in Figure 3 corresponds to the maximum spot-transit effect. The three other panels demonstrate several other possible light curve deviations.

According to equation (5), the time dependence of the deviation (i.e. \vec{r}_L -dependence) can be separated from the dependence on the spot contrast (μ through B_D). It follows that changing the contrast affects only the amplitude of the deviation curve during a microlensing event, not its shape. To see the change in amplitude as a function of μ , it is sufficient

³ A dark spot can produce a positive effect, because the amplification (3) is normalized by the lower intrinsic flux from the spotted star.

to look at the change in the maximum deviation during an event⁴, $\delta_M = \max_t |\delta[\vec{r}_L(t)]|$. The dependence of δ_M on spot contrast is shown in Figure 4. In this generic example an $\epsilon = 13.23$ lens has a zero impact parameter and a $r_s = 0.1$ spot is centered on the source ($s = 0$). The dependence is steep for $\mu < 5$, but changes only slowly for $\mu > 10$. Values of μ between 2 and 10 are thought to be typical of stellar dark spots, roughly corresponding to ΔT of 250 to 1000 K, which is at the high end of spots observed in active stars. In most of the calculations presented here we use $\mu = 10$ to study the maximum spot effect.

In a similar way we can study the dependence on the Einstein radius. We find that δ_M grows while $\epsilon < 1$, but remains practically constant for $\epsilon > 2$. This saturation is due to the linear dependence of amplification on ϵ close to the light curve peak ($|\vec{r}_L| \ll \epsilon$) for sufficiently large ϵ . The ratio of amplifications in equation (5) then cancels out the ϵ -dependence.

The effect of spot size on δ_M is illustrated by the following two figures. Figure 5 demonstrates the detectability of spots on the stellar surface for various combinations of spot radius and impact parameter. Spots centered in the black regions will produce a maximum effect higher than 5%. Those centered in the grey cross-hatched areas have $\delta_M < 2\%$, and thus would be difficult to detect. We can draw several conclusions for dark spots with sufficient contrast (here $\mu = 10$). As a rule of thumb, small spots with radii $r_s \leq 0.15$ could be detected ($\delta_M > 2\%$) if the lens passes within $\sim 1.5 r_s$ of the spot center. Larger spots with $r_s \geq 0.2$ can be detected over a large area of the source during source-transit events, and possibly even marginally during near-transit events (e.g. $p \sim 1.2$). As a further interesting result, the maximum effect a spot of radius r_s (within the studied range) can have during a transit event is numerically roughly $\delta_M \sim r_s$, irrespective of the actual impact parameter value. For example, a spot with radius 0.05 can have a maximum effect of 5%, and an $r_s = 0.2$ spot can cause a 19% deviation.

Figure 6 is closely related to Figure 5. For a fixed impact parameter we plotted contours of the minimum radius of a spot (centered at the particular position) necessary to be detectable ($\delta_M > 2\%$). As hinted above, during any transit event a spot with $r_s \simeq 0.3$ located practically anywhere on the projected surface of the source will produce a detectable signature on the light curve.

Turning to the case of a bright spot, we can use the same approach as above with a negative decrement B_D in formula (5), corresponding to contrast parameter $\mu < 1$. As noted earlier, a change in the contrast affects only the scale but not the shape of the deviation curves. The only difference for a bright spot is a change in sign of the deviation

⁴ The maximum deviation is therefore parametrized by p and β instead of \vec{r}_L .

due to negative B_D . Therefore the geometry of the contour plots in Figure 2 remains the same, only the contour values and poles are changed. The maximum deviation at the position of the bright spot is now positive, the weaker opposite peak is negative. Changing the sign of the deviation in Figure 3 in fact gives us deviation curves for a bright spot in the same geometry with $\mu \doteq 0.5$ instead of $\mu = 10$. This correspondence can be seen from Figure 4, where both these values have a same maximum effect δ_M . Unlike in the case of a dark spot, there is mathematically no upper limit on the relative effect of a bright spot. A very bright spot would achieve high magnification and dominate the light curve, acting as an individual source with radius r_s .

3. Change in Spectral Line Profiles

Studying spectral effects requires computing light curves for a large set of wavelengths simultaneously. Changes in the observed spectrum of a spotless source star due to microlensing are described in HSL. Most individual absorption lines respond in a generic way - they appear less prominent when the lens is crossing the limb of the source, and become more prominent if the lens approaches the center of the source. The effect can be measured by the corresponding change in the equivalent width of the line.

The use of sensitive spectral lines can maximize the search for spots and active regions on the surfaces of microlensed stars (Sasselov 1997). Similar techniques are widely known and used in the direct study of the Sun. One example is observing the bandhead of the CH radical at 430.5 nm, which provides very high contrast to surface structure (Berger et al. 1995). This method will require spectroscopy of the microlensing event, but could be very rewarding.

For red giants such as the M95-30 source, the $H\alpha$ line will be sensitive to active regions on the surface (which often, but not always, accompany spots). To demonstrate the effect, we computed the $H\alpha$ profile using a 5-level non-LTE solution for the hydrogen atom in a giant atmosphere, as described in HSL. We use the same M95-30 source model as in the previous calculations ($T=3750$ K, $\log g=0.5$), for the active region ($\Delta T \sim 800$ K) we use the line profile of a $\log g=2$ giant with a chromosphere similar to that of β Gem.

In Figure 7 we show a time sequence of the changing profile of $H\alpha$ distorted by an $r_s = 0.1$ active region on the surface of the star. In the calculation we used the M95-30 Einstein radius and zero impact parameter. The presence of the $H\alpha$ -bright region leads to a noticeable change in the line profile; in its absence the change is considerably weaker. In this particular case, more pronounced wings as well as wing emission can be seen when the lens passes near the active region.

4. Discussion

The small spot model used in this work has obvious limitations. For example, the constant brightness decrement assumption is not adequate close to the limb, and spots can have various shapes and brightness structure (umbra, penumbra). However, most of these problems are not significant for sufficiently small spots, and will not change the general character of the obtained results. The dependence of the deviation on the spotless brightness profile $B(r)$ was also neglected in the study (except for its effect on the contrast μ). According to expression (5), it can be expected to have a weak effect on the amplitude, and due to the spotless amplification (1) an even weaker effect on the shape of the amplification deviation curve of a microlensing event.

More importantly, it should be noted that the deviations computed in this paper are deviations from the light curve of the underlying spotless source in the same lensing geometry. This is not necessarily the best-fit spotless light curve for the given event. In practice, this will limit the range of the marginally detectable events with $\delta_M \sim 2\%$. Good photometry and spectroscopy combined with an adequate model atmosphere for the source star can reduce this problem.

The range of detectability will also be reduced if we consider the duration of the observable effect. If this effect occurs over a too short period, it could easily pass undetected. Source-crossing times in microlensing transit events can reach several days (~ 3.5 d in M95-30 with $p \sim 0.7$; corresponding source-radius crossing time ~ 2.5 d). As seen from Figures 2 and 3, an effect $\delta > 2\%$ can then last hours to days. Dense light curve sampling during any transit event can therefore lead to detections or at least provide good constraints on the presence of spots on the source star. Note that these timescales are too short to expect effects due to intrinsic changes in the spots or their significant motion in the case of red giant sources, which have typically slow rotation speeds. These effects should be considered only in long timescale events with smaller sources - events with an inherently low probability.

The source star can be expected to have more than just a single spot. The lensed flux is linear in $B(\vec{r})$, therefore it can be again split into terms corresponding to individual spots and the underlying spotless source. An analysis similar to the one in this paper can then be performed. The single spot case provides helpful insight into the general case, even though the relative amplification deviation is not a linear combination of individual spot terms.

The presence of spots on microlensed stars (e.g. red giants) could complicate the interpretation of light curves which may be distorted due to a planetary companion of the lens (Gaudi & Gould 1997, Gaudi & Sackett 1999). A dark spot could be confused

with the effect of a planet perturbing the minor image of the source, while a bright spot ($\mu < 1$) can resemble a major image perturbation (see Figure 3). However, the spot effect is always localized near the peak region of the light curve, which is itself affected by the finite source size. Deviations due to planetary microlensing are usually expected as perturbations offset from the peak of a simple point-source light curve. It would be therefore sufficient to look for signatures of limb-crossing during the event, by photometry in two or more spectral bands or by spectroscopy. High-magnification planetary microlensing events, in which the source crosses the perturbed caustic near the primary lens (Griest & Safizadeh 1998), can however prove to be more difficult to distinguish, as they can also have a similar limb-crossing signature for a sufficiently large source.

5. Summary

Stellar spots can be detected by observations of source-transit microlensing events. The amplification deviation due to the spot can be positive as well negative, depending on the relative configuration of the lens, source and spot. In the small spot case ($r_s \lesssim 0.2$) studied here, we find that dark spots with radii $r_s \lesssim 0.15$ can cause deviations $\delta_M > 2\%$ if the lens passes within $1.5 r_s$ of the spot center. Larger spots with $r_s \sim 0.2$ can be detected over a large area of the surface of the source during any transit event, in some cases even in near-transit events. Numerically we find that the maximum effect of a dark spot with sufficient contrast is roughly equal to the fractional spot radius r_s , when the spot is directly crossed. On the other hand a very bright spot can dominate the shape of the light curve. The obtained results on the relative amplification deviation are largely independent of the Einstein radius of the lens in the range $u > 2$; most microlensing events toward the Galactic Bulge fall well within this range. The presence of spots and especially active regions can also be detected efficiently by observing the changing profiles of sensitive spectral lines during microlensing events with a small impact parameter.

Light curves due to sources with spots can resemble in some cases the effect of a low-mass companion of the lens. Good photometry and spectroscopy will suffice to distinguish the two in most cases. Currently operating microlensing follow-up projects such as PLANET (Albrow et al. 1998) and GMAN (Becker et al. 1997) can perform high-precision photometry with high sampling rates, both are sensitive enough to put constraints on the presence of spots in future source-transit events. As a result, over a few observing seasons statistical evidence for spots on red giants could be obtained, making an important contribution to our theoretical understanding of stellar atmospheres.

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REFERENCES

- Albrow, M., et al. 1998, *ApJ*, 509, 687
- Alcock, C., et al. 1997, *ApJ*, 491, 436
- Becker, A., et al. 1997, *AAS*, 191, 83.05
- Berger, T. E., Schrijver, C. J., Shine, R. A., Tarbell, T. D., Title A. M., & Scharmer, G. 1995, *ApJ*, 454, 531
- Di Benedetto, G. P., & Bonneau, D. 1990, *ApJ*, 358, 617
- Gaudi, B. S., & Gould, A. 1997, *ApJ*, 486, 85
- Gaudi, B. S., & Sackett, P. D. 1999, *ApJ*, submitted (astro-ph/9904339)
- Griest, K., & Safizadeh, N. 1998, *ApJ*, 500, 37
- Guinan, E. F., Guedel, M., Kang, Y. W., & Margheim, S. 1997, in *Variable Stars and the Astrophysical Returns of Microlensing Surveys*, ed. R. Ferlet, J. P. Maillard, & B. Raban (Gif-sur-Yvette: Editions Frontières), 339
- Heyrovský, D., & Loeb, A. 1997, *ApJ*, 490, 38
- Heyrovský, D., Sasselov, D., & Loeb, A. 1999, *ApJ*, submitted (astro-ph/9902273) (HSL)
- Hummel, C. A., Armstrong, J. T., Quirrenbach, A., Buscher, D. F., Mozurkewich, D., Elias, N. M. II, & Wilson, R. E. 1994, *AJ*, 107, 1859
- Paczynski, B. 1996, *ARA&A*, 34, 419
- Sasselov, D. D. 1997, in *Variable Stars and the Astrophysical Returns of Microlensing Surveys*, ed. R. Ferlet, J. P. Maillard, & B. Raban (Gif-sur-Yvette: Editions Frontières), 141
- Schwarzschild, M. 1975, *ApJ*, 195, 137
- Udalski, A., Szymański, M., Kałużny, J., Kubiak, M., Mateo, M., & Krzemiński, W. 1995, *Acta Astron.*, 45, 1
- Uitenbroek, H., Dupree, A. K., & Gilliland, R. L. 1998, *AJ*, 116, 2501

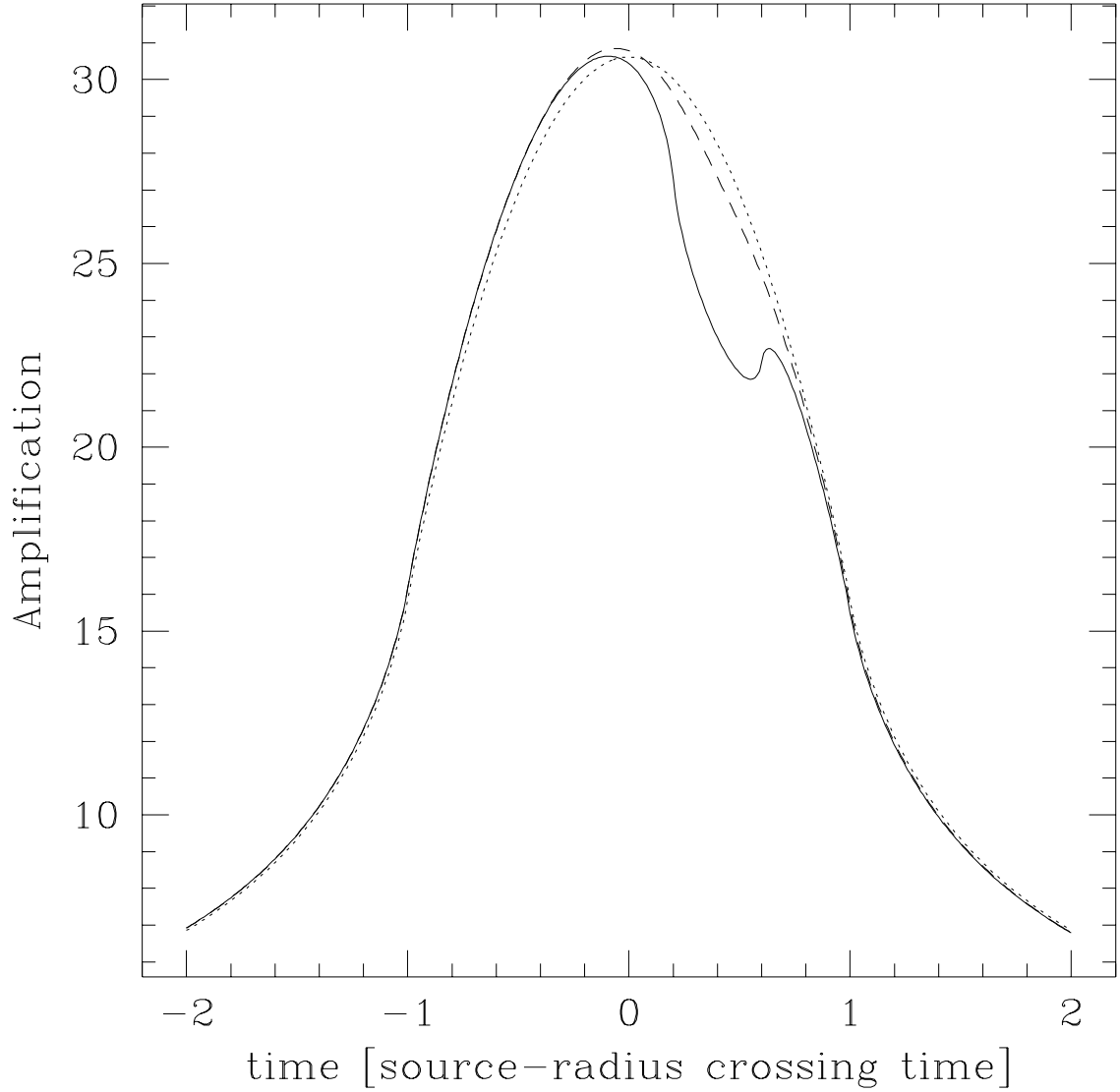


Fig. 1.— Microlensing light curves of a star with a spot (lens with $\epsilon = 13.23$, zero impact parameter). Solid line - spot with radius 0.2 centered at $s = 0.4$ on the lens path; dashed line - same spot offset by 0.3 perpendicular to lens path; dotted line - no spot (for comparison). The underlying source is a 3750 K red giant observed in the V-band, spot contrast $\mu = 10$.

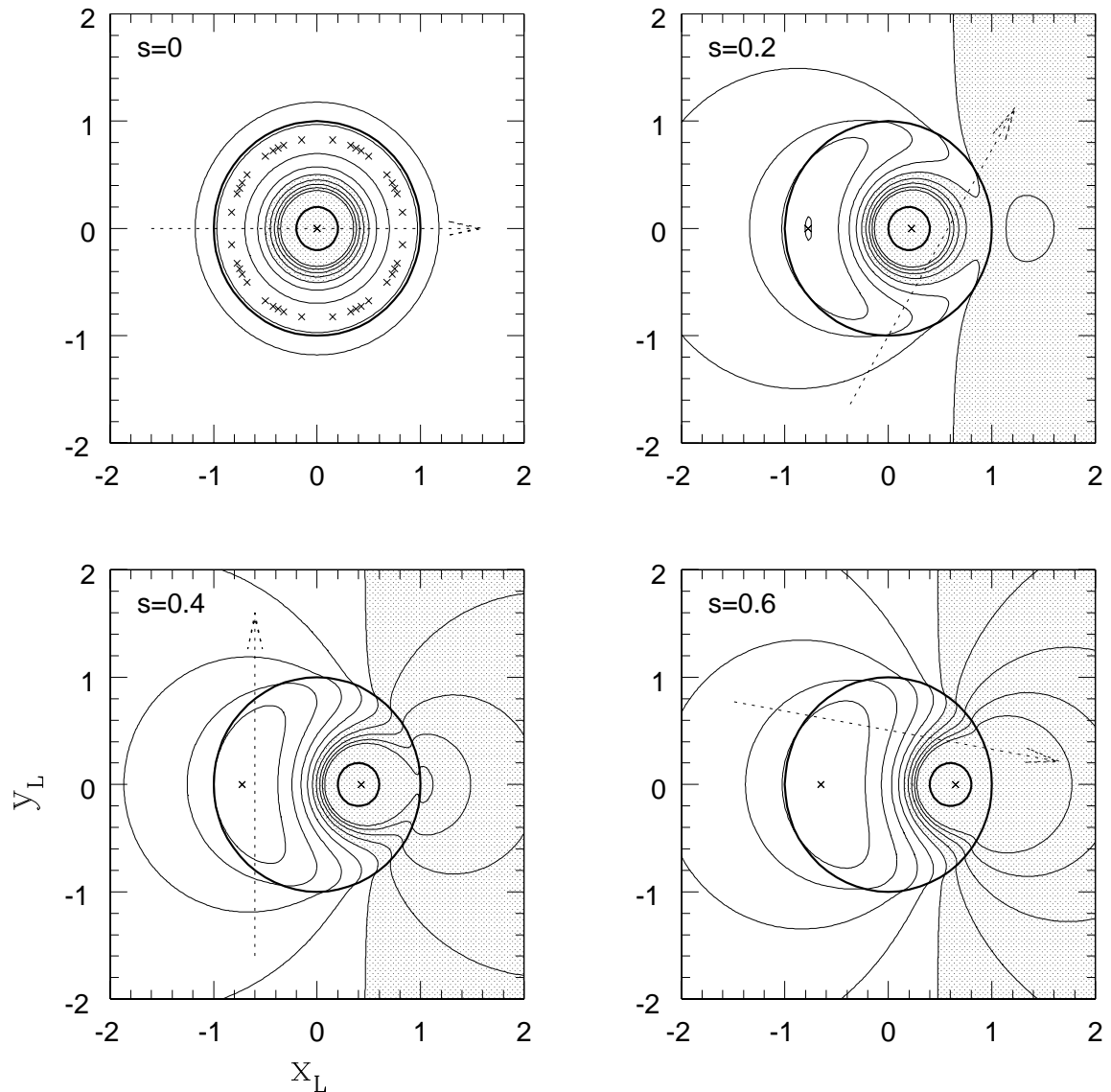


Fig. 2.— Contour plots of relative amplification deviation δ as a function of lens position (Einstein radius $\epsilon = 13.23$). The two bold circles in each plot represent the source with an $r_s = 0.2$, $\mu = 10$ spot. The four plots correspond to different spot positions, $s = 0, 0.2, 0.4, 0.6$. The crosses identify the positions with maximum negative and positive effects, the region with a negative effect is shaded. In the $s = 0$ case the positive maximum is extended along a circle. Contours are spaced by 0.5% decreasing toward the spot and increasing toward the positive maximum. The minimum contour plotted here is -2%, all positive contours are plotted. Deviation curves for the lens paths marked by dotted arrows are shown in Figure 3.

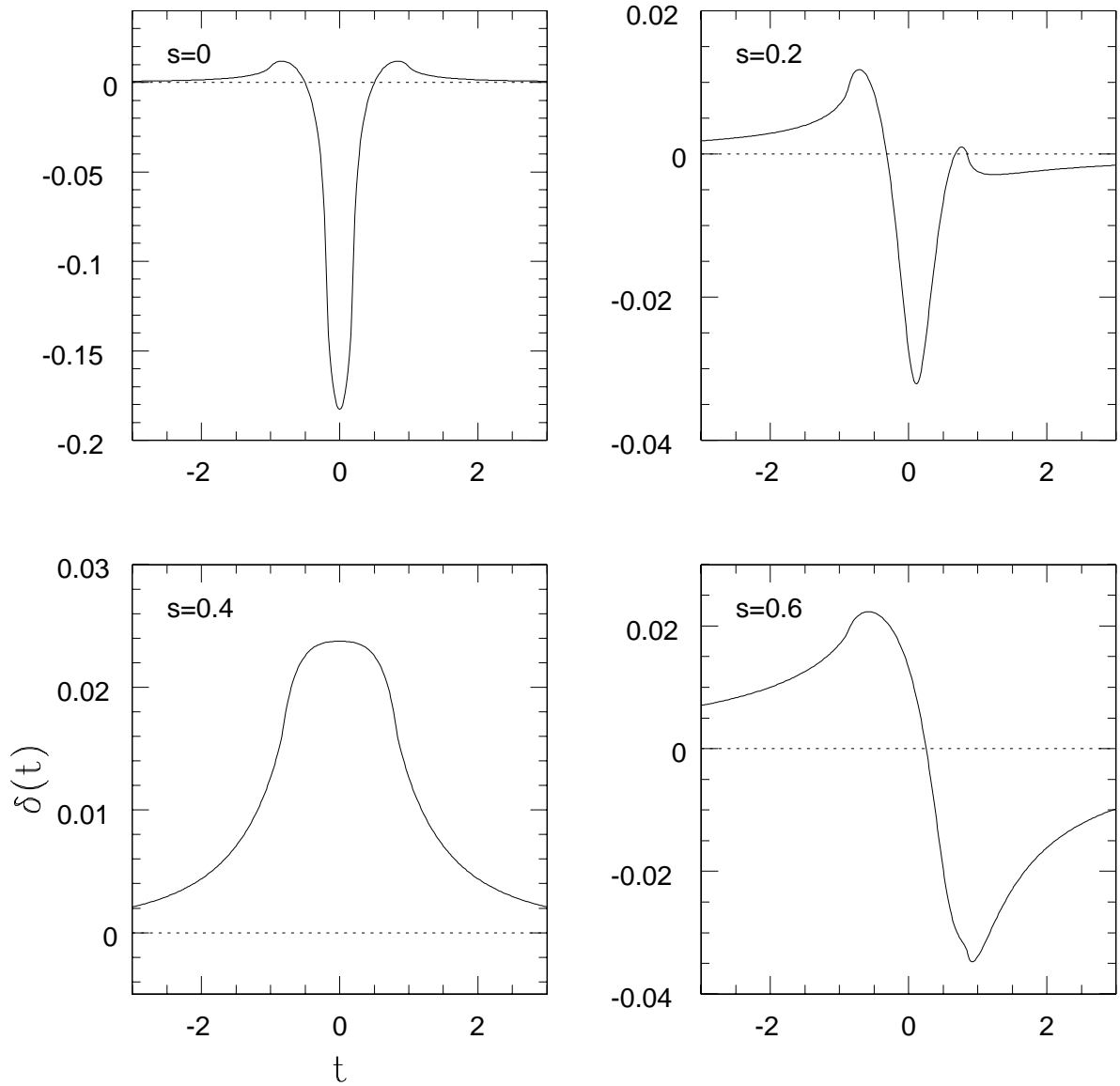


Fig. 3.— Relative light curve deviation δ as a function of time t (in units of source-radius crossing time) for four lens paths marked in the corresponding panels of Figure 2. As in the previous figure, Einstein radius $\epsilon = 13.23$, spot radius $r_s = 0.2$ and spot contrast $\mu = 10$. The four spot position values s label the upper left corner of the panels. Lens trajectory parameters for the upper left panel are $(p, \beta) = (0, 0^\circ)$, upper right $(0.5, 60^\circ)$, lower left $(-0.6, 90^\circ)$ and lower right $(-0.5, -10^\circ)$. Vertical inversions $\delta \rightarrow -\delta$ correspond to deviation curves for a bright spot with $\mu \doteq 0.5$ in the same configurations.

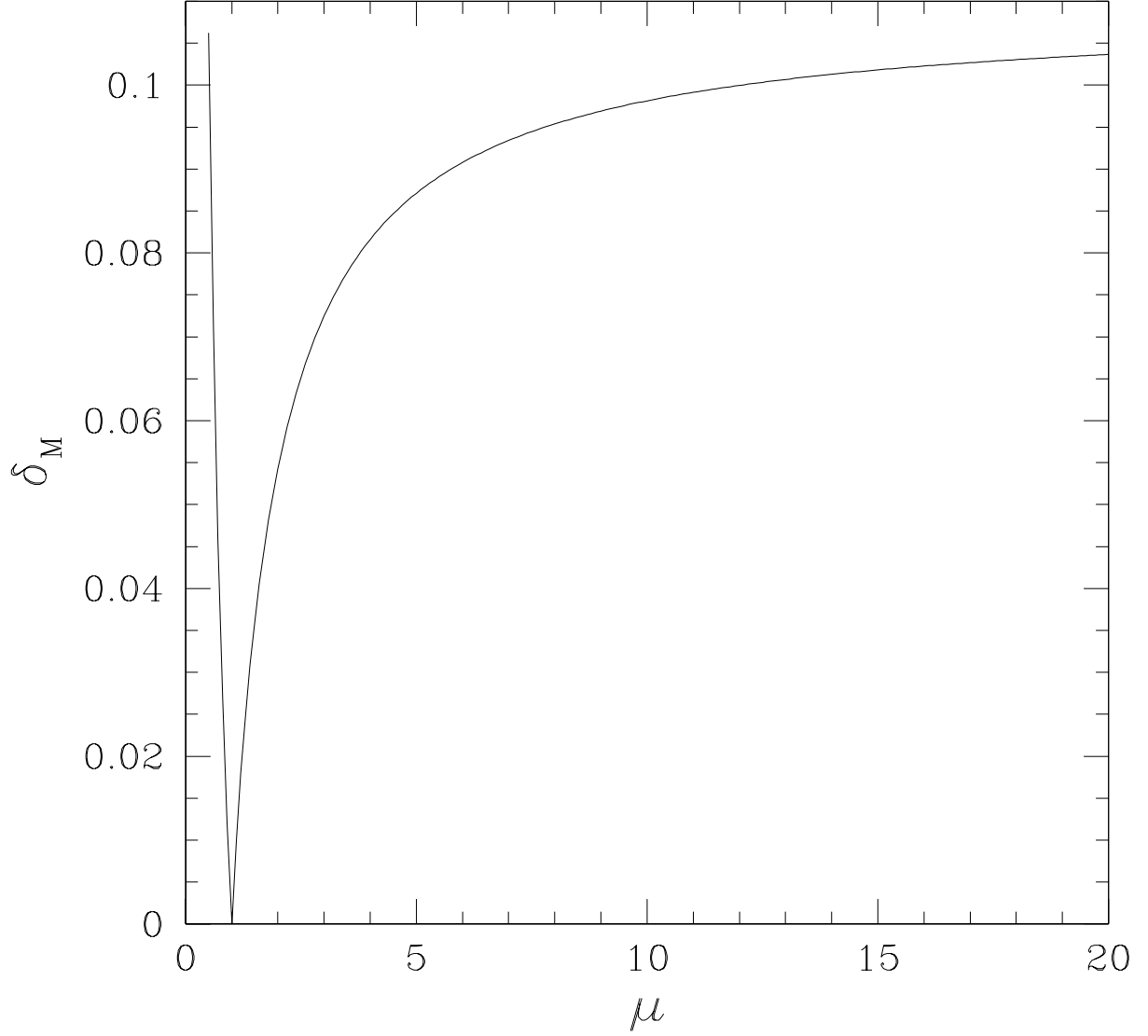


Fig. 4.— Dependence of the maximum deviation δ_M on spot contrast μ . This example corresponds to a zero impact parameter transit of a source with an $r_s = 0.1, s = 0$ spot by an $\epsilon = 13.23$ lens.

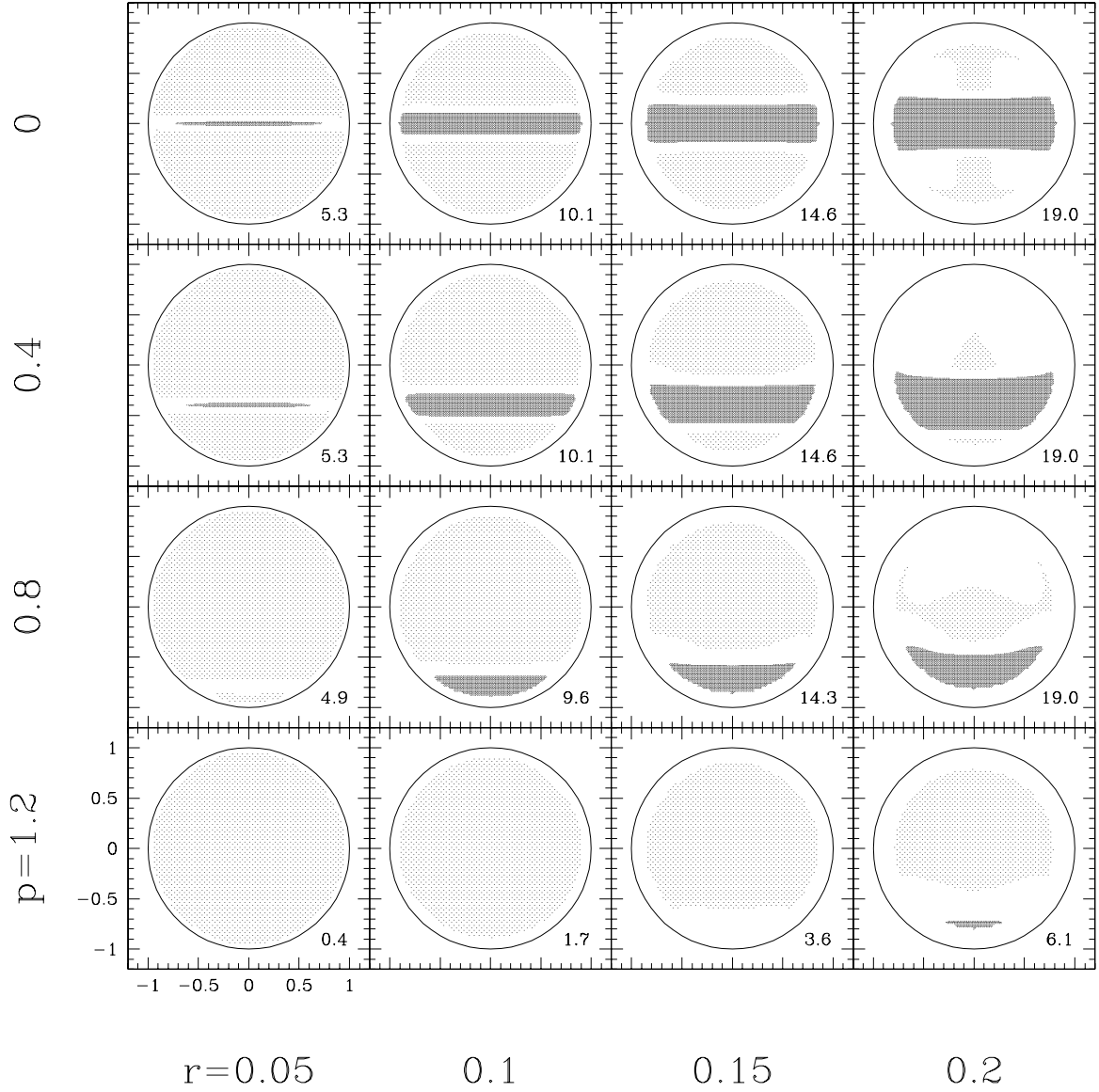


Fig. 5.— Maximum spot effect δ_M color-coded as a function of spot position on the stellar surface for different impact parameters p and spot sizes r_s . In all cases the $\epsilon = 13.23$ lens passes horizontally in the lower half of the disk. Spot contrast is kept constant $\mu = 10$. Spots centered in the black regions cause $\delta_M > 5\%$, those centered in the grey regions $\delta_M < 2\%$. The maximum effect δ_M in percent is noted in each of the panels.

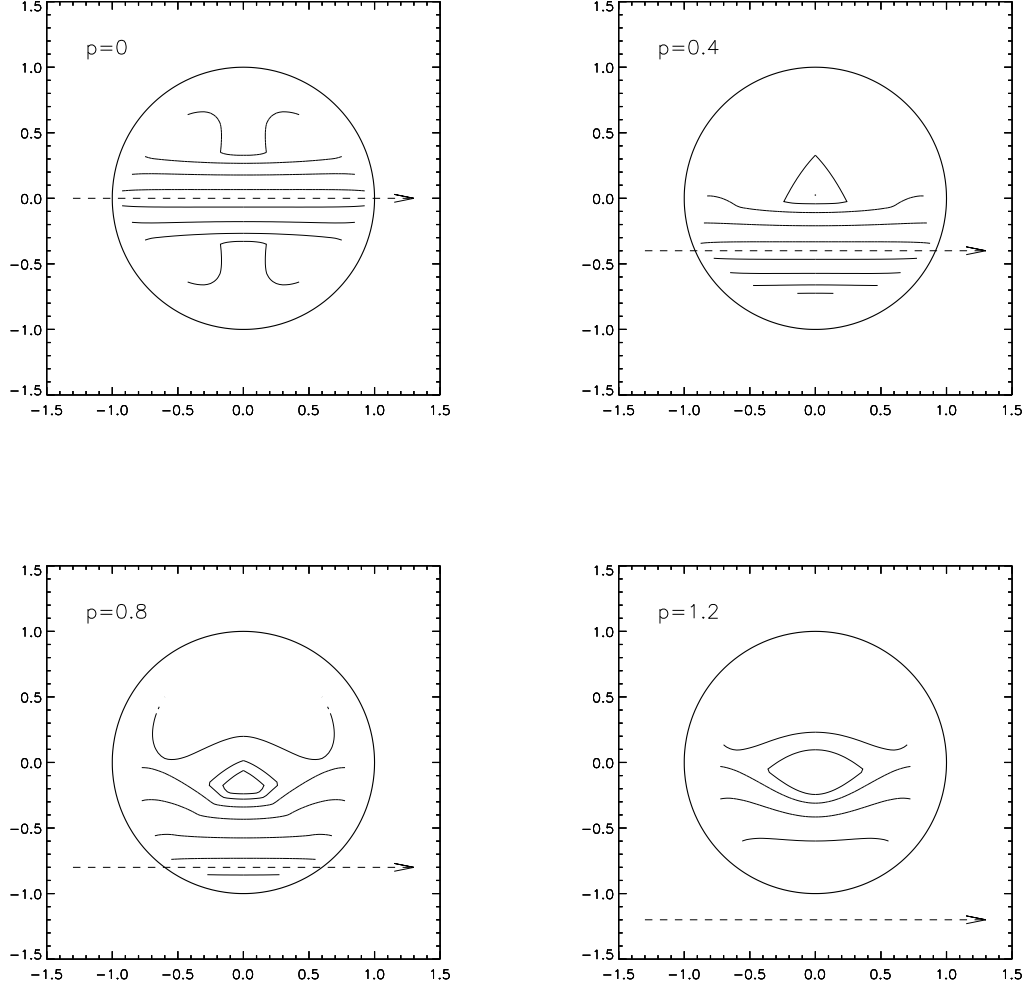


Fig. 6.— Contours of minimum detectable spot size as a function of spot position in microlensing events with impact parameters $p = 0, 0.4, 0.8, 1.2$ as marked in the panels. Detectability condition used here is $\delta_M > 2\%$. Dashed arrows mark the lens trajectories. Contour values increase away from the lens path on both sides with 0.05 spacing - for $p = 0, 0.4$ values range from $r_s = 0.05$ to $r_s = 0.2$; for $p = 0.8$ from $r_s = 0.05$ to $r_s = 0.3$ (inner closed contour); for $p = 1.2$ from $r_s = 0.15$ to $r_s = 0.3$ (closed contour). As in Figure 5, $\epsilon = 13.23$ and $\mu = 10$.

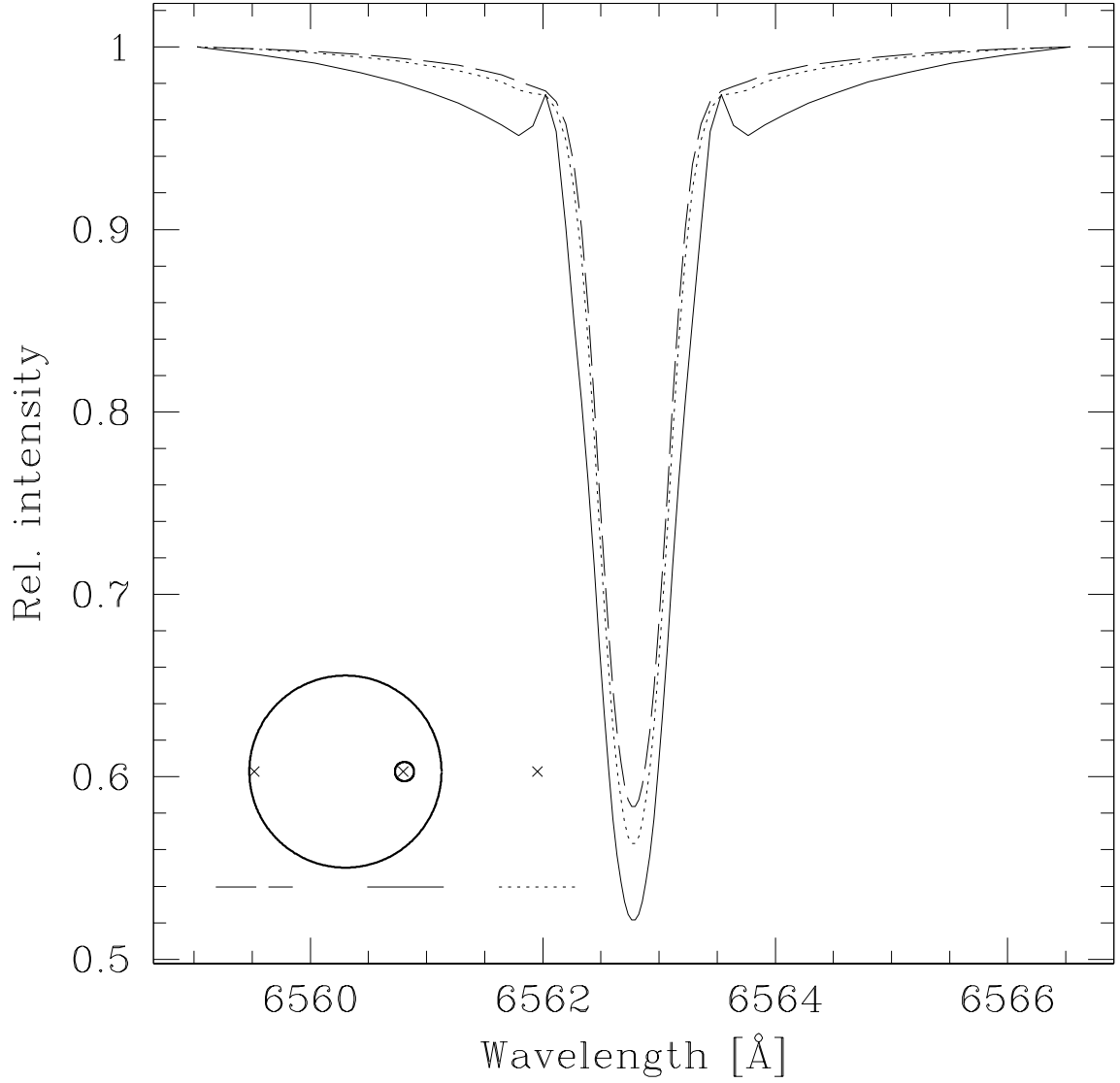


Fig. 7.— $H\alpha$ line profiles of a microlensed star with an active region for different lens positions. The bold sketch in the lower left illustrates the stellar disk with an active region of radius $r_s = 0.1$. The three lens positions are marked by crosses. Einstein radius $\epsilon = 13.23$.

